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Physics of GaN-based High-Power Lasers

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Abstract

Advanced device simulation is used to analyze performance and device physics of milestone nitride laser diodes. These lasers exhibit the highest room-temperature continuous-wave output power measured thus far. The laser model self-consistently combines band structure and free-carrier gain calculations with two-dimensional simulations of wave guiding, carrier transport, and heat flux. Material parameters used in the model are carefully evaluated. Excellent agreement between simulations and measurements is achieved. The maximum output power is limited by electron leakage into the p-doped ridge. Leakage escalation is caused by strong self-heating, gain reduction, and elevated carrier density within the quantum wells. Improved heat-sinking is predicted to allow for a significant increase of the maximum output power.

Introduction

Fabry-Perot laser diodes emitting at 400 nm wavelength are investigated which exhibit the highest output power measured thus far (420 mW) [1]. The active region includes two InGaN quantum wells, an AlGaN electron stopper layer, GaN waveguide layers, and superlattice cladding layers (Fig. 1). Advanced laser simulation is used to analyze internal physical processes, to reveal performance limitations, and to explore optimization options. The laser model self-consistently combines 6x6 **kp** band structure and gain calculations with two-dimensional simulations of wave guiding, carrier transport, and heat flux [2]. However, the optical gain mechanism in InGaN quantum wells of real lasers is still not fully understood. It may be strongly affected by a non-uniform Indium distribution. Internal polarization fields tend to separate quantum confined electrons and holes, thereby reducing optical gain and spontaneous emission. However, screening by electrons and holes is expected to suppress quantum well polarization fields at high power operation. The high carrier density also eliminates excitons. On the other hand, many-body models predict significant gain enhancement at high carrier densities. Considering all the uncertainties in calculating the gain of real InGaN quantum wells, we here start with a simple free carrier gain model, including a Lorentzian broadening function with 0.1ps scattering time. The resulting gain characteristics are plotted in Fig. 2 for different temperatures.
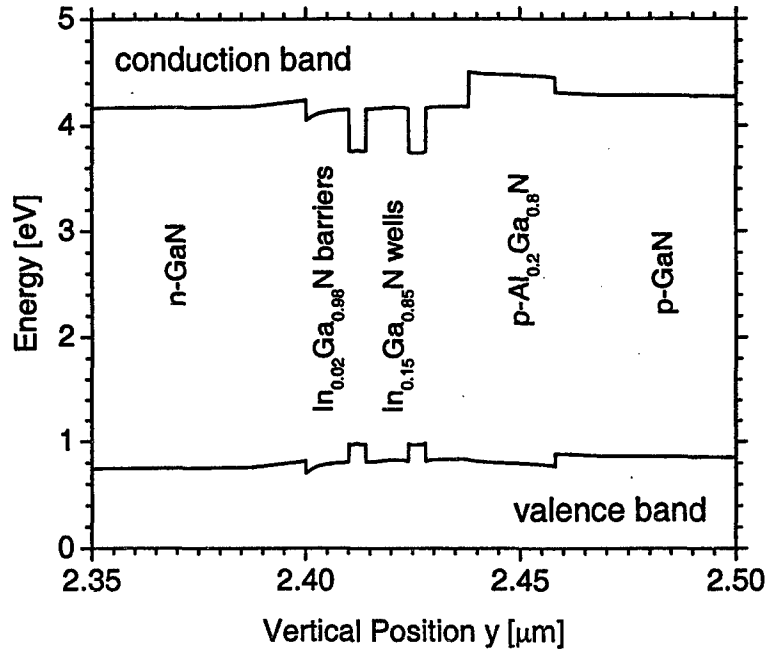
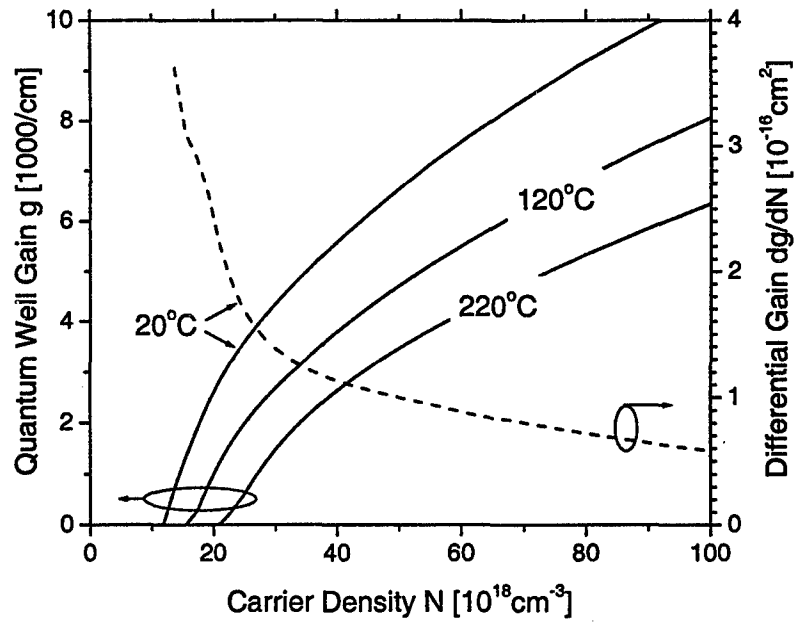Fig. 1: Energy band diagram of the active region near lasing threshold.

Fig. 2: Gain vs. carrier density at different temperatures (solid) and differential gain vs. carrier density at room temperature (dashed).

Comparison to Measurements

All material parameters used in the model are carefully evaluated. Excellent agreement with measured current-voltage (IV) and light-current (LI) characteristics is achieved (Fig. 3). The IV fit indicates a low p-contact resistance in these devices. The LI fit leads to the following internal device parameters: 12 /cm internal modal loss, 0.5 ns defect recombination lifetime within the quantum wells, and 75 K/W thermal resistance. All three numbers are within the expected range which confirms the accuracy of the laser model.
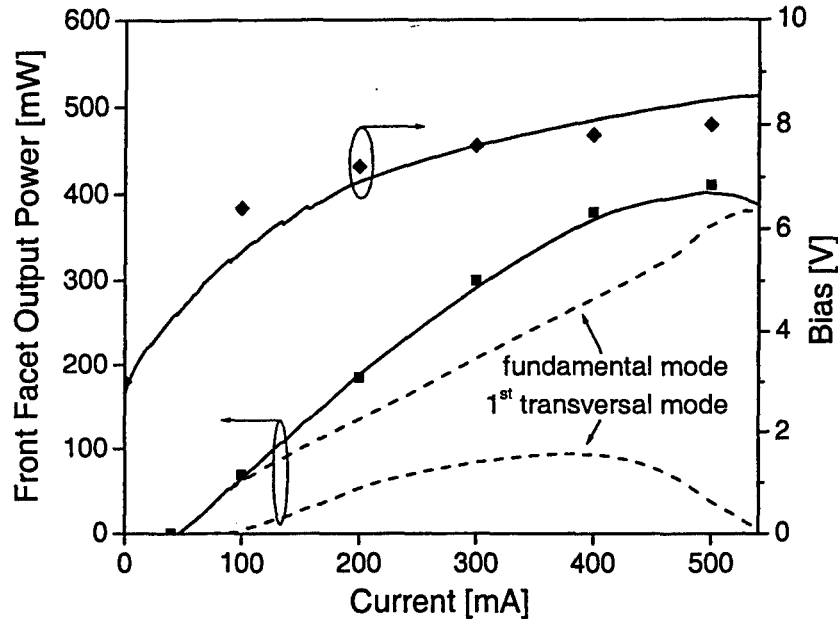

Fig. 3: Current-voltage and light-current characteristics (dots – measurement, lines – simulation).

Power Limiting Mechanisms

The output power roll-off of laser diodes is typically attributed to the self-heating in continuous-wave operation. The data in Fig. 3 indicate the generation of about 4 W heat power at the lasing power maximum. Considering 75 K/W thermal resistance, it is not surprising that a strong internal heating is calculated of about $\Delta T = 300$ K. The different heat sources are illustrated in Fig. 4. Joule heat in the highly resistive p-doped regions dominates the power budget by far. The much smaller contribution from phonons generated by defect recombination is partially compensated for by Thomson cooling, which represents the phonon absorption by carriers. Photon absorption is of minor importance. The strong self-heating reduces the optical gain (cf. Fig. 2) which leads to a substantial increase in quantum well carrier density. This triggers an escalation of electron leakage from the quantum wells into the p-doped side of the laser (Fig. 5) causing the measured power roll-off. Polarization charges are found to hardly affect the maximum power as they are screened by the high carrier density in the quantum wells.
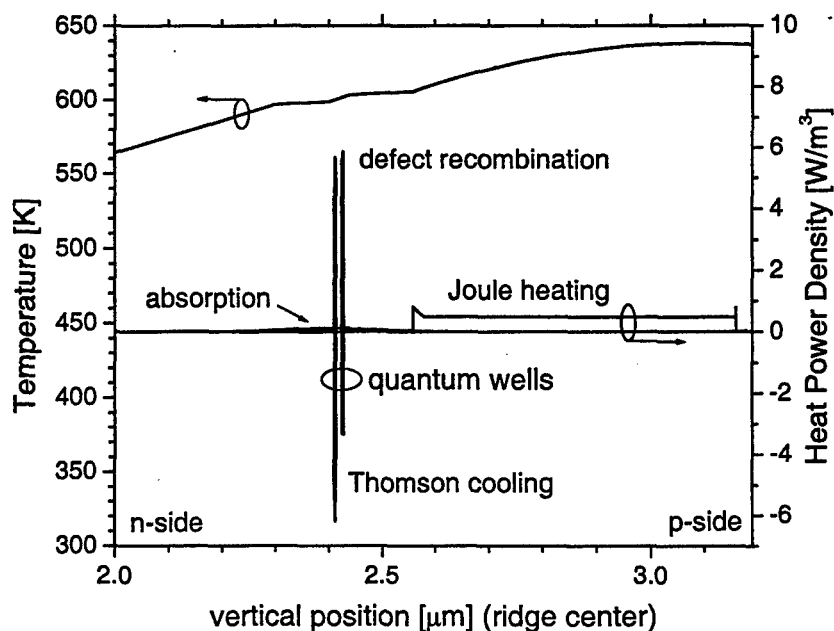
Fig. 4: Vertical profile of internal temperature and heat sources at maximum power.
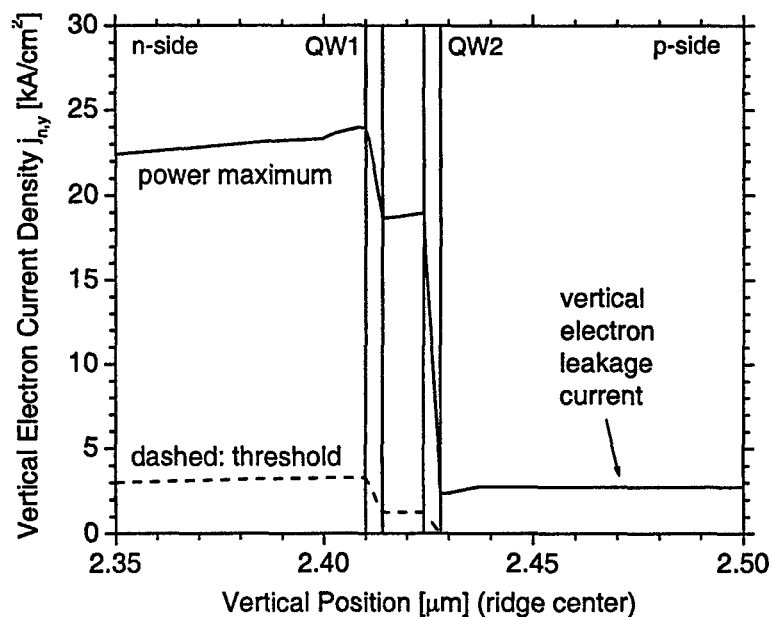

Fig. 5: Vertical profile of electron current density showing electron leakage into the p-side at the power maximum.

Laser Optimization

Reduction of the self-heating is the key to higher lasing power. This can be achieved by lowering the heat power generation or by improved heat dissipation. The electrical resistance of the p-doped layers constitutes the main heat source but it cannot be easily reduced since higher p-doping causes a lower hole mobility. Improved heat sinking has recently been demonstrated by replacing the sapphire substrate with copper [3]. In our simulation, we simply eliminate the external thermal resistance of 30K/W, which reduces the total thermal resistance to 45 K/W. The resulting LI characteristic exhibits almost double the maximum output power (Fig. 6).
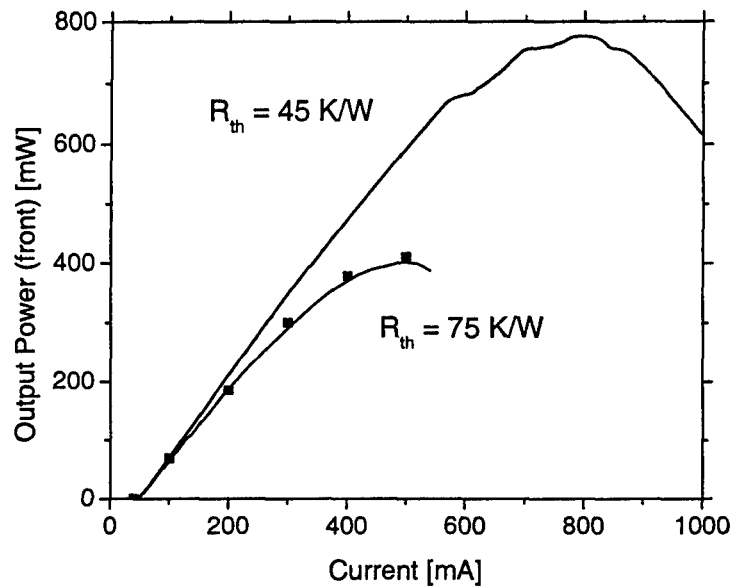
Fig. 6: Simulation of the light-current characteristic with reduced thermal resistance R_{th} in comparison to original curve from Fig. 3.

References

[1]   S. Nakamura et al., *Japanese Journal of Applied Physics, Part 2,*   vol. 37, p. L627 (1998).

[2]   LASTIP by Crosslight Software, 2001.

[3]   M. Kneissl et al., *IEEE Journal of Selected Topics in Quant. Electronics,* vol. 7, p. 188 (2001).